Electroweak Corrections at the LHC

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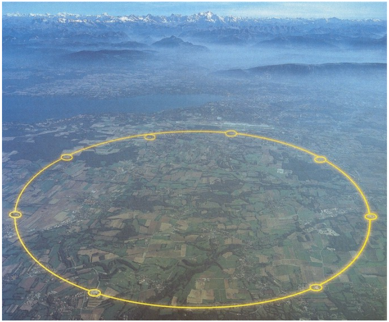
Outline

Finding the Higgs, New Physics, Black Holes, ?

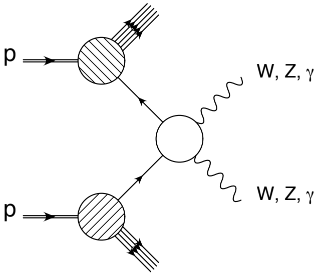
Large Hadron Collider (LHC)

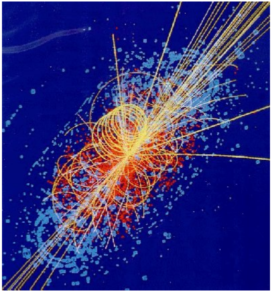
- proton - proton collider
- $E_{cm} \sim 14$ TeV
- increased luminosity



proton-proton collisions

- strong interaction dynamics complicates computation
- asymptotic freedom allows for perturbative calculation of parton-parton collisions.
- look at parton-parton subprocesses, and turn into cross-sections using parton distribution functions





Parton Processes

Typical LHC processes being studied such as jet production, t-quark pair production, squark pair production proceed via energetic partonic processes

$$qq \to qq, \quad q\bar{q} \to q\bar{q}, \quad q\bar{q} \to t\bar{t}, \quad q\bar{q} \to \tilde{q}\tilde{q}^*$$

with $Q \sim \sqrt{s}$ of order (few) TeV.

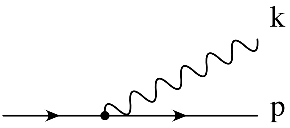
Final state invariant masses are much smaller than Q.

Describe these using SCET. Work in the regime

$$s \sim -t \sim -u \sim Q^2$$

(Hard Scattering)

Radiation



The intermediate propagator is

$$\frac{1}{(p+k)^2} = \frac{1}{2p\cdot k} = \frac{1}{E\omega(1-\cos\theta)}$$

Singularities as:

$\omega \to 0$ (soft singularity) and $\theta \to 0$ (collinear singularity).

QED

Collinear singularity regulated by fermion mass $\rightarrow \log Q^2/m^2$.

Soft singularity: need to put a detector resolution: $\log Q^2/\Delta^2$.

Exclusive processes have $\log^2 Q^2/m^2$ at large Q.

QCD

In QCD: look at inclusive processes. Add up processes with collinear or soft radiation into IR safe observables. Then one does not get the double logarithms.

The total cross-section $e^+e^- \rightarrow$ hadrons

$$R = 1 + \frac{\alpha_s(Q)}{\pi}$$

Sudakov Double Logarithms

There are no electroweak singlet targets or beams, so all processes behave like the exclusive case and have double logs.

M. Ciafaloni, P. Ciafaloni and D. Comelli, PRL 84 (2000) 4810

Typical form of the radiative corrections:

$$\frac{\alpha}{4\pi \sin^2 \theta_W} \log^2 \frac{s}{M_{W,Z}^2} \sim 0.15$$

for $\sqrt{s} \sim 4$ TeV.

Can be much larger. Need to be combined with the QCD radiative corrections, which are 5 times larger.

Size of Corrections

These corrections are large, and must be resummed. The purely electroweak (i.e. not including QCD) corrections can be 40% at LHC energies.

The QCD corrections are enormous (factors of 50) and must be included at least to NLL order. [This is known]

Strongly energy dependent.

Previous Work

M. Ciafaloni, P. Ciafaloni and D. Comelli

V. S. Fadin, L. N. Lipatov, A. D. Martin and M. Melles

B. Jantzen, J. H. Kuhn, A. A. Penin and V. A. Smirnov

M. Beccaria, F. M. Renard and C. Verzegnassi

A. Denner and S. Pozzorini

M. Hori, H. Kawamura and J. Kodaira

W. Beenakker and A. Werthenbach

This talk based on

J. Chiu, F. Golf, R. Kelley, A.M, PRL 100 (2008) 021802

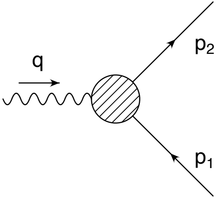
J. Chiu, F. Golf, R. Kelley, A.M, PRD 77 (2008) 053004

J. Chiu, R. Kelley, A.M, arXiv:0806.1240

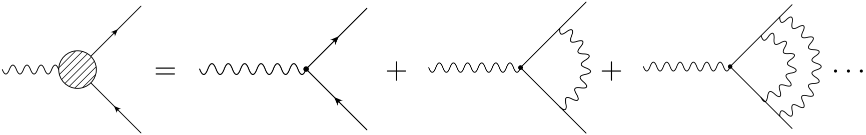
Sudakov Form Factor

- $(Q^2 \equiv -q^2 = -(p_2 - p_1)^2)$,

$$F_E(Q)\left[\bar{u}(p_2)\gamma^\mu u(p_1)\right] = \langle p_2 | \, J^\mu_{EM}(q) \, | p_1 \rangle =$$



- If coupling strength is small we calculate $F_E(Q^2)$ perturbatively in powers of $\alpha = \frac{e^2}{4\pi}$.



- $F_E(Q)$ for $Q^2 \gg m_e^2 \sim 0$ is called the Sudakov Form Factor
- We will work with the on-shell form factor, i.e. an S-matrix element for scattering.
- The off-shell form-factor with $p_i^2 \neq m_i^2$ is also considered in the literature. There is a factor of 2 in the double-logarithm between the two cases.
- pair production: analytically continue $Q^2 \to -q^2 - i0^+$,

$$\log \frac{Q^2}{\mu^2} \to \log \frac{q^2}{\mu^2} - i\pi$$

- In QED, look at $\log Q^2/m_e^2$ terms. Here we study $\log Q^2/M_{W,Z}^2$ corrections.

IREE (InfraRed Evolution Equation) inspired approach — a well-motivated guess as to the structure of the corrections.

Previous computations done with all gauge bosons having a common mass M. Conceptual problems with symmetry breaking and $SU(2) \times U(1)$ mixing which lead to $M_W \neq M_Z$.

$$\log \frac{Q^2}{M^2} \to \log \frac{Q^2}{M_W^2} + \log \frac{Q^2}{M_Z^2} + \log \frac{Q^2}{M_\gamma^2} \qquad \text{but } M_\gamma = 0$$

Can address the issues using effective field theory methods.

Agrees with previous fixed order computations to 2 loops by Jantzen, Kühn, Penin and Smirnov

Can include m_t — multiscale problem with m_t and M.

General perturbative structure of $F_E(Q)$

$$\mathrm{L} = \log \mathrm{Q}^2/\mathrm{M}^2$$

(Each term has a coefficient)

$$\begin{aligned} F_E(Q) = \Big[1 \quad &+ \quad \alpha^1\left(\mathrm{L}^2 + \mathrm{L}^1 + \mathrm{L}^0\right) && \text{LO + NLO} \\ &+ \quad \alpha^2\left(\mathrm{L}^4 + \mathrm{L}^3 + \mathrm{L}^2 + \mathrm{L}^1 + \mathrm{L}^0\right) && \text{N}^2\text{LO} \\ &+ \quad \alpha^3\left(\mathrm{L}^6 + \mathrm{L}^5 + \mathrm{L}^4 + \mathrm{L}^3 + \mathrm{L}^2 + \mathrm{L}^1 + \mathrm{L}^0\right)\Big] && \text{N}^3\text{LO} \\ &+ \quad \alpha^4\left(\mathrm{L}^8 + \mathrm{L}^7 + \mathrm{L}^6 + \mathrm{L}^5 + \cdots + \mathrm{L}^0\right)\Big] && \text{N}^4\text{LO} \end{aligned}$$

The α^n term has powers of L up to L^{2n}.

Structure of series

- The $\alpha \mathsf{L}^2$, $\alpha^2 \mathsf{L}^4$, $\alpha^3 \mathsf{L}^6$ series is called $\mathsf{LL}_{\mathsf{FO}}$.
- The $\alpha \mathsf{L}$, $\alpha^2 \mathsf{L}^3$, $\alpha^3 \mathsf{L}^5$ series is called $\mathsf{NLL}_{\mathsf{FO}}$.

The series for $\log F_E(Q^2)$ takes a simpler form

$$\begin{aligned}\log F_E \quad &= \quad \alpha\left(\mathsf{L}^2 + \mathsf{L} + \mathsf{L}^0\right) \\ &\quad + \alpha^2\left(\mathsf{L}^3 + \mathsf{L}^2 + \mathsf{L} + \mathsf{L}^0\right) \\ &\quad + \alpha^3\left(\mathsf{L}^4 + \ldots + \mathsf{L}^0\right) + \ldots\end{aligned}$$

with the α^n term having power of L upto L^{n+1}.

$$\log F_E \quad = \quad \mathsf{L}\, f_0(\alpha \mathsf{L}) + f_1(\alpha \mathsf{L}) + \alpha\, f_2(\alpha \mathsf{L}) + \ldots$$

Counting of Logs

Only get L^{n+1} at order α^n, so there are far fewer terms.

$$\log F_E = \mathsf{L}\, f_0(\mathsf{L}) + f_1(\alpha \mathsf{L}) + \alpha\, f_2(\alpha \mathsf{L}) + \ldots$$

RGE counting: f_0 is LL, f_1 is NLL, etc.

If we then expand to get F_E and look (for example) at order α^2:

- $\alpha^2 \mathsf{L}^4$ is LL ($\mathrm{LL}_{\mathrm{FO}}$),
- $\alpha^2 \mathsf{L}^3$ is NLL ($\mathrm{NLL}_{\mathrm{FO}}$),
- $\alpha^2 \mathsf{L}^2$ is NNLL ($\mathrm{NNLL}_{\mathrm{FO}}$),
- $\alpha^2 \mathsf{L}$ is NNLL ($\mathrm{N}^3\mathrm{LL}_{\mathrm{FO}}$)

mismatch in number of N's increases at higher orders in α.

Infrared Evolution Equation

Collins

$$\log F_E(Q^2) = \log F_0(\alpha(M))$$

$$+ \int_{M^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2} \left[\zeta(\alpha(\mu)) + \xi(\alpha(M)) + \int_{M^2}^{\mu^2} \frac{\mathrm{d}\mu'^{\,2}}{\mu'^{\,2}} \Gamma(\alpha(\mu')) \right]$$

ξ integral can be done.
F_0, ζ, ξ and Γ have the expansions

$$\begin{aligned} F_0(\alpha) &= 1 + F_0^{(1)}\alpha + F_0^{(2)}\alpha^2 + \ldots \\ \Gamma(\alpha) &= \Gamma^{(1)}\alpha + \Gamma^{(2)}\alpha^2 + \ldots \\ \zeta(\alpha) &= \zeta^{(1)}\alpha + \zeta^{(2)}\alpha^2 + \ldots \\ \xi(\alpha) &= \xi^{(1)}\alpha + \xi^{(2)}\alpha^2 + \ldots . \end{aligned}$$

SCET Form

$$\log F_E(Q^2) = C(a(Q)) + D_0(a(M)) + D_1(a(M)) \log \frac{Q^2}{M^2}$$
$$+ \int_Q^M \frac{\mathrm{d}\mu}{\mu} \left[A(a(\mu)) \log \frac{\mu^2}{Q^2} + B(a(\mu)) \right]$$

- C: matching at Q
- $A \log \mu^2/Q^2 + B$: SCET anomalous dimension
- $D_0 + D_1 \log Q^2/M^2$: matching at M
- There is a $\log Q$ in the matching at M

Mapping between SCET and IREE

$$
\begin{aligned}
\frac{1}{2}A(a) &= \Gamma(a) \\
D_1(a) &= \xi(a) \\
-\frac{1}{2}B(a) + \frac{1}{2}\frac{\partial C(a)}{\partial a}\beta_a(a) &= \zeta(a) \\
C(a) + D_0(a) &= \log F_0(a).
\end{aligned}
$$

The log in the low scale matching, D_1, is ξ.

Resummation

$$A = \begin{pmatrix} 1 & & & & \\ \alpha L^2 & \alpha L & \alpha & & \\ \alpha^2 L^4 & \alpha^2 L^3 & \alpha^2 L^2 & \alpha^2 L & \alpha^2 \\ \alpha^3 L^6 & & \ldots & & \\ \vdots & & & & \end{pmatrix}$$

In the leading-log regime $L \sim 1/\alpha$, the various terms are of order

$$A = \begin{pmatrix} 1 & & & & \\ \frac{1}{\alpha} & 1 & \alpha & & \\ \frac{1}{\alpha^2} & \frac{1}{\alpha} & 1 & \alpha & \alpha^2 \\ \frac{1}{\alpha^3} & & \ldots & & \\ \vdots & & & & \end{pmatrix}.$$

Resummation: Exponentiated Form

Exponentiated form:

$$\log A = \begin{pmatrix} \alpha L^2 & \alpha L & \alpha & & \\ \alpha^2 L^3 & \alpha^2 L^2 & \alpha^2 L & \alpha^2 & \\ \alpha^3 L^4 & \alpha^3 L^3 & \alpha^3 L^2 & \alpha^3 L & \alpha^3 \\ \alpha^4 L^5 & & \ldots & & \\ \vdots & & & & \end{pmatrix}$$

In the leading-log regime:

$$\log A = \begin{pmatrix} \frac{1}{\alpha} & 1 & \alpha & & \\ \frac{1}{\alpha} & 1 & \alpha & \alpha^2 & \\ \frac{1}{\alpha} & 1 & \alpha & \alpha^2 & \alpha^3 \\ \frac{1}{\alpha} & & \ldots & & \\ \vdots & & & & \end{pmatrix} .$$

Resummation: Exponentiated Form

$$\begin{aligned} \log A &= \frac{1}{\alpha} f_0 + f_1 + \alpha f_2 + \ldots \\ &= \frac{1}{\alpha}\left[f_0 + \alpha f_1 + \alpha^2 f_2 + \ldots \right] \end{aligned}$$

so that f_1 and f_2 are corrections to $\log A$. However,

$$\begin{aligned} A &= \exp\left[\frac{1}{\alpha} f_0 + f_1 + \alpha f_2 + \ldots\right] \\ &= e^{\frac{1}{\alpha} f_0} \times e^{f_1} \times e^{\alpha f_2} \times \ldots \end{aligned}$$

Must include the LL and NLL series. QCD is in this regime, and the corrections are a factor of 50.

Electroweak corrections are in the leading-log-squared regime, with $\alpha \mathsf{L}^2 \sim 1$.

Resummation: Electroweak

$$A = \begin{pmatrix} 1 & & & & \\ 1 & \alpha^{1/2} & \alpha & & \\ 1 & \alpha^{1/2} & \alpha & \alpha^{3/2} & \alpha^2 \\ 1 & & & \ldots & \\ & & \vdots & & \end{pmatrix}$$

and in exponentiated form

$$\log A = \begin{pmatrix} 1 & \alpha^{1/2} & \alpha & & \\ \alpha^{1/2} & \alpha & \alpha^{3/2} & \alpha^2 & \\ \alpha & \alpha^{3/2} & \alpha^2 & \alpha^{5/2} & \alpha^3 \\ \alpha^2 & & & \ldots & \\ \vdots & & & & \end{pmatrix}.$$

Big difference from the QCD case. All the large terms can be included by using a one-loop RG improved computation.

So can include all effects by doing a two-loop QCD plus one-loop EW renormalization group improved computation.

Included $M_W \neq M_Z$, $\gamma - Z$ mixing, m_t effects, and Higgs radiative corrections. Numerically, the results we have obtained have errors below 1%.

SCET

Describes energetic particles with small invariant mass.

Define $p^+ = E - p_z$, $p^- = E + p_z$. The the power counting is

$$p^- \sim Q \qquad p^+ \sim Q\lambda^2 \qquad p_\perp \sim Q\lambda \qquad \Rightarrow \qquad p^2 \sim Q^2\lambda^2$$

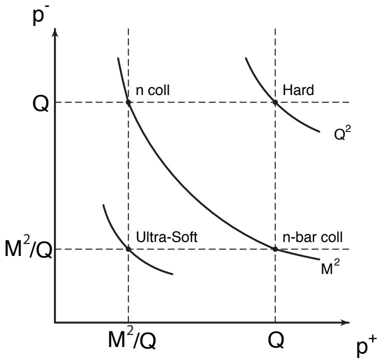
for particles moving along the z-direction. n-collinear

For particles moving in the $-z$-direction, swap $p^+ \leftrightarrow p^-$. $\bar{n}$-collinear

Have n-collinear, $\bar{n}$-collinear, and ultrasoft gluons.

SCET degrees of freedom (modes)

- Light Cone Coordinates:
- Hard Modes: $p^2 \sim Q^2$
  integrated out
- Collinear modes: $p^2 \sim M^2$
- Ultra-Soft modes: $p^2 \sim M^4/Q^2$
  do not contribute



Outline of Calculation

Full Theory

$C(Q, \mu)$ ——————————————— $\mu = Q$

SCET ($M = 0$)

$$\Big\downarrow \gamma_{\mathrm{SCET}}$$

SCET (with Mass)

$D(M, \mu)$ ——————————————— $\mu = M$

SCET (without gauge bosons)

Outline of Calculation

1. match at Q onto SCET with gauge bosons

$$\langle p_2 | \hat{\mathcal{O}}_{full} | p_1 \rangle = \exp[C(Q)] \langle p_2 | \hat{\mathcal{O}}_{SCET} | p_1 \rangle$$

2. run from $Q \to M$:

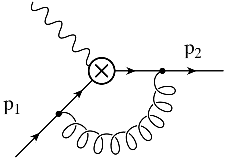
$$\exp[C(M)] = \exp[C(Q)] \exp\left[\int_Q^M \frac{d\mu}{\mu} \gamma_{SCET}(\mu)\right]$$

3. match at M onto SCET without gauge bosons

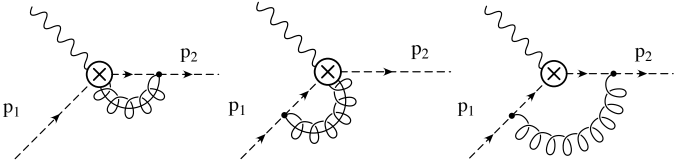
$$\begin{aligned} \langle p_2 | \hat{\mathcal{O}}_{SCET} | p_1 \rangle &= \exp[D(M)] \langle p_2 | \hat{\mathcal{O}}_{SCET\ w/o\ W's} | p_1 \rangle \\ D(M) &= D_0(\alpha(M)) + D_1(\alpha(M)) \log \frac{Q^2}{M^2} \end{aligned}$$

High scale matching: $\mu \sim Q$

- full theory:



- EFT:



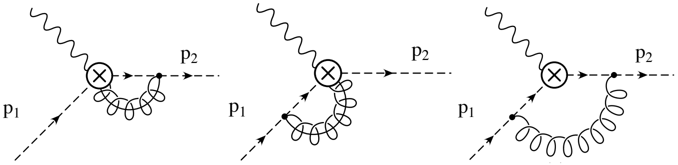
Same as for DIS, since small scales such as M can be neglected.

- Matching at Q:

$$
\begin{aligned}
\mathsf{L}_Q &= \log \frac{Q^2}{\mu^2} \\
c(\mu) &= \exp C(\mu) \\
C(\mu) &= a(\mu)\, C_F \left(-\mathsf{L}_Q^2 + 3\mathsf{L}_Q + \frac{\pi^2}{6} - 8\right)
\end{aligned}
$$

No large logs if μ is of order Q, e.g. if $\mu = \eta Q$, then

$$
\mathsf{L}_Q = \log \frac{1}{\eta^2}
$$



- Compute running between Q and M using SCET anomalous dimension.
- From UV divergences, so independent of IR scales such as M,
- same as DIS

$$\begin{aligned} \mu \frac{\mathrm{d}c(\mu)}{\mathrm{d}\mu} &= \gamma(\mu) c(\mu) \\ \gamma(\mu) &= a(\mu)\, C_F \,[4\mathsf{L}_Q - 6] \end{aligned}$$

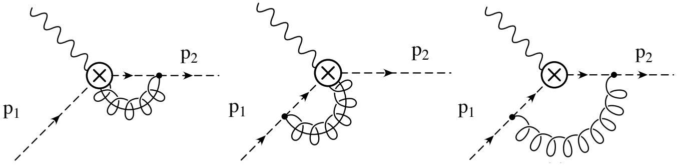
$$\log c(M) - \log c(Q) \;=\; \int_Q^M \frac{\mathrm{d}\mu}{\mu}\,\gamma(\mu)$$

An additive shift in $C(\mu)$, i.e. in $\log F_E$.

The last step is to integrate out the massive gauge bosons at $\mu = M$.

Low scale matching: $\mu \sim M$

- EFT (SCET with gauge bosons):



- EFT (SCET without gauge bosons):

NONE

Finite part gives the matching correction:

$$\exp D \quad = \quad a\, C_F \left[2\mathsf{L}_M \mathsf{L}_Q - \mathsf{L}_M^2 - 4\mathsf{L}_M + \frac{9}{2} - \frac{5\pi^2}{6} \right]$$

There is a $\log Q^2/M^2$ term in the matching at $\mu \sim M$.

Take $\mu = M$, then $\mathsf{L}_M = 0$ and the $\log Q$ term vanishes. But this is a fake. If $\mu = \eta M$, then

$$\mathsf{L}_Q \mathsf{L}_M \to \left(\log \frac{Q^2}{M^2} + \log \frac{1}{\eta^2} \right) \log \frac{1}{\eta^2}$$

Single log in low scale matching

There is a single log in the matching.

At two-loop order, it does not vanish even if $\mu = M$.

It cannot be moved to the anomalous dimension, because it depends on particle masses. There is a piece of the form

$$\mathrm{Cl}_2(\pi/3), \qquad \mathrm{Cl}_2(x) = \sum_{1}^{\infty} \frac{\sin nx}{n^2}$$

for massive particles at two loops, which is absent for massless particles.

Log summation by RGE

Normal RGE:

$$\alpha^n \left(L^n, L^{n-1}, \ldots L^2, L \right)$$

summed using RGE equations — n terms at order α^n.

Sudakov (SCET) RGE — wanted to sum:

$$\alpha^n \left(L^{2n}, L^{2n-1}, \ldots L^2, L \right)$$

but can only sum

$$\alpha^n \left(L^{2n}, L^{2n-1}, \ldots L^2, \cancel{L} \right)$$

which sums $2n - 1$ terms instead of $2n$. Not so bad.

Agrees with the known results. Can reproduce the known two-loop fixed order computations using a one-loop computation plus RGE: $\alpha^2 \times \mathrm{L}^4, \mathrm{L}^3, \mathrm{L}^2$.

It is now simple to compute other results, which have not been done:

Other operators, e.g. $\bar{\psi}\psi$, $\phi^\dagger\phi$, $\phi^\dagger\psi$ etc. (SCET for scalars)

Can include mass effects — two fermions have masses m_1 and m_2, and sum logs of m_i.

Can include Higgs fields and Yukawa couplings, and compute for the standard model, including the top-quark Yukawa coupling.

Do the case M_H, M_W, and M_Z all different, and treat electroweak mixing.

$\mathcal{O}$	$C(\mu)/C_F$	$\gamma_{EFT}(\mu)/C_F$	$D(\mu)/C_F$
$\bar{\psi}\psi$	$-\mathsf{L}_Q^2 + \frac{\pi^2}{6} - 2$	$4\mathsf{L}_Q - 6$	$-\mathsf{L}_M^2 + 2\mathsf{L}_M\mathsf{L}_Q - 3\mathsf{L}_M + \frac{9}{2} - \frac{5\pi^2}{6}$
$\bar{\psi}\gamma^\mu\psi$	$-\mathsf{L}_Q^2 + 3\mathsf{L}_Q + \frac{\pi^2}{6} - 8$	$4\mathsf{L}_Q - 6$	$-\mathsf{L}_M^2 + 2\mathsf{L}_M\mathsf{L}_Q - 3\mathsf{L}_M + \frac{9}{2} - \frac{5\pi^2}{6}$
$\bar{\psi}\sigma^{\mu\nu}\psi$	$-\mathsf{L}_Q^2 + 4\mathsf{L}_Q + \frac{\pi^2}{6} - 8$	$4\mathsf{L}_Q - 6$	$-\mathsf{L}_M^2 + 2\mathsf{L}_M\mathsf{L}_Q - 3\mathsf{L}_M + \frac{9}{2} - \frac{5\pi^2}{6}$
$\phi^\dagger\phi$	$-\mathsf{L}_Q^2 + \mathsf{L}_Q + \frac{\pi^2}{6} - 2$	$4\mathsf{L}_Q - 8$	$-\mathsf{L}_M^2 + 2\mathsf{L}_M\mathsf{L}_Q - 4\mathsf{L}_M + \frac{7}{2} - \frac{5\pi^2}{6}$
$i(\phi^\dagger D^\mu\phi - D^\mu\phi^\dagger\phi)$	$-\mathsf{L}_Q^2 + 4\mathsf{L}_Q + \frac{\pi^2}{6} - 8$	$4\mathsf{L}_Q - 8$	$-\mathsf{L}_M^2 + 2\mathsf{L}_M\mathsf{L}_Q - 4\mathsf{L}_M + \frac{7}{2} - \frac{5\pi^2}{6}$
$\bar{\psi}\phi$	$-\mathsf{L}_Q^2 + 2\mathsf{L}_Q + \frac{\pi^2}{6} - 4$	$4\mathsf{L}_Q - 7$	$-\mathsf{L}_M^2 + 2\mathsf{L}_M\mathsf{L}_Q - \frac{7}{2}\mathsf{L}_M + 4 - \frac{5\pi^2}{6}$

Note there is a factorization structure in the EFT

All $\bar{\psi}\psi$ are equal, all $\phi^\dagger\phi$ are equal, $\bar{\psi}\phi$ is the average in the EFT.

Factorization Structure

For massive fermions also have a factorization form:

$$\Gamma_{12}(Q^2, 1, 2) \quad = \quad \Gamma_{12}(2p_1 \cdot p_2) + f_1(m_1) + f_2(m_2)$$

where $\Gamma(Q)$ is independent of particle type, and f_i only depends on the properties of particle i (including whether it is a scalar or fermion).

$$\Gamma_{12}(2p_1 \cdot p_2) \quad = \quad a \log(2p_1 \cdot p_2) + b$$

Factorization up to a calculable single log term.

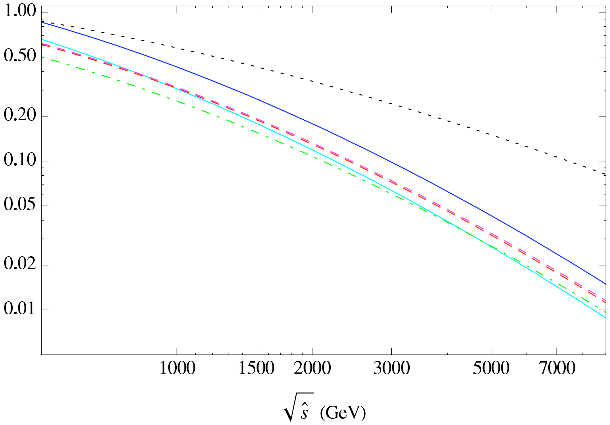
top quark with Higgs corrections:

$m_t - m_b$ is large, and breaks $SU(2) \times U(1)$ symmetry. If one uses a sequence of theories with $M_H > m_t > M_Z > M_W$, then a mess.

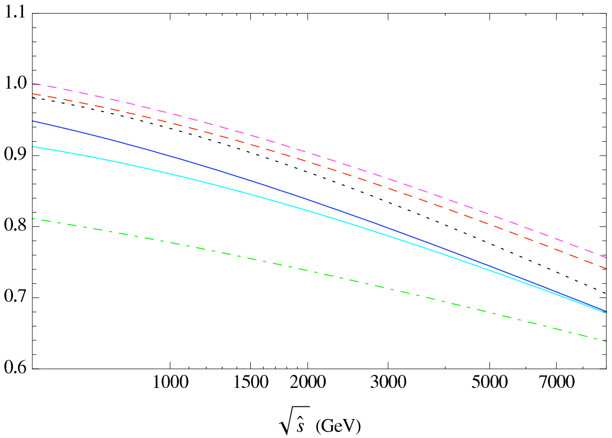
But instead, can integrate them all out at a common μ.

Go from $SU(3) \times SU(2) \times U(1)$ directly to $SU(3) \times U(1)$, and a theory with SCET $Q^{(t)}$, t_R and b_R fields to one with SCET b_L, b_R fields and HQET t_L, t_R fields.

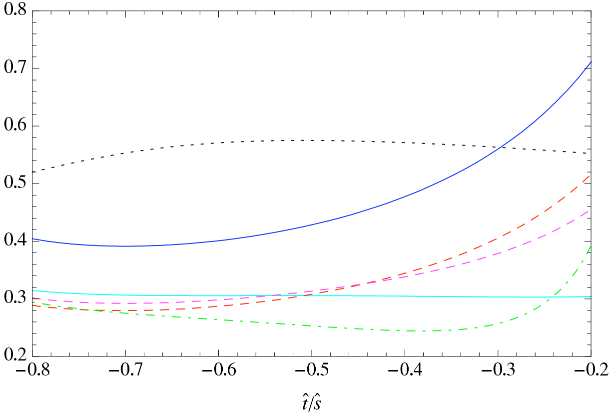
Then compute observables as before. For cross-sections, the SCET field matrix elements in the proton are the Collins-Soper parton distribution functions. For final states, construct jet observables, or t-observables, etc.



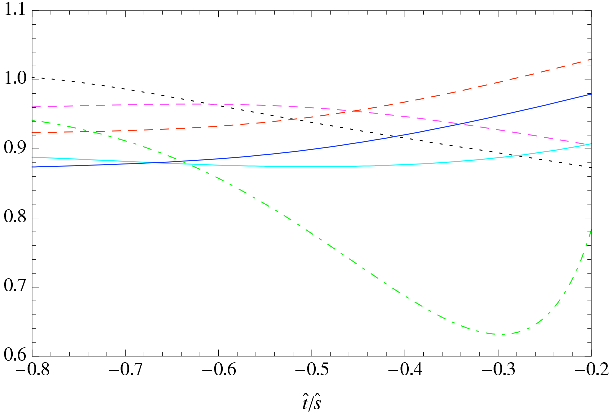
Rates for $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta) as a function of $\sqrt{\hat{s}}$ in GeV at $\theta = 90^\circ$, normalized to their tree-level values without any radiative corrections. Note the logarithmic scale.



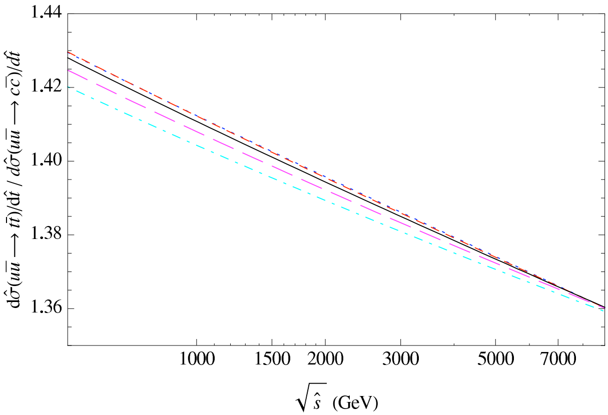
Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta) as a function of $\sqrt{\hat{s}}$ in GeV at $\theta = 90^\circ$. The large corrections for $u\bar{u} \to d\bar{d}$ arise from the t-channel W exchange graph.



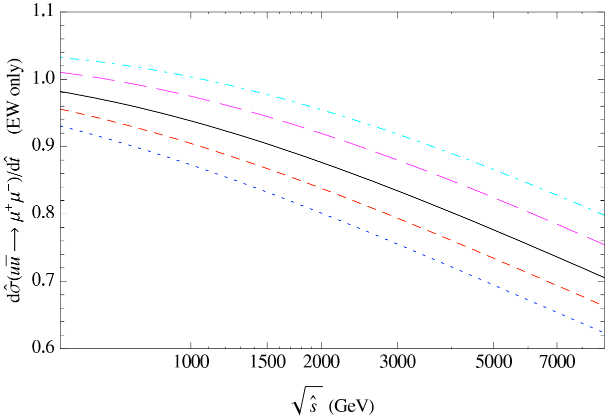
Rates for $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta)as a function of $-\hat{t}/\hat{s}$ for $\sqrt{\hat{s}} = 1$ TeV, normalized to their tree-level values without any electroweak corrections.



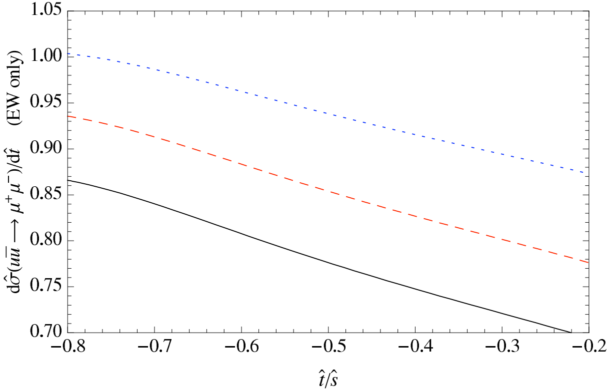
Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta) as a function of $-\hat{t}/\hat{s}$ for $\sqrt{\hat{s}} = 1$ TeV. The large corrections for $u\bar{u} \to d\bar{d}$ arise from the t-channel W exchange graph.



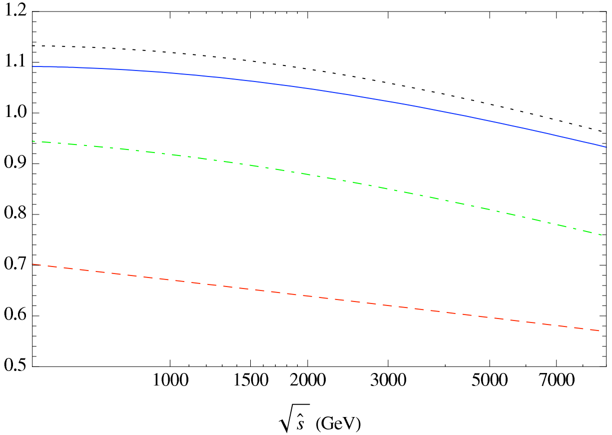
The ratio $(u\bar{u} \to t\bar{t})/(u\bar{u} \to c\bar{c})$ at $\hat{t} = -0.2\hat{s}$, (dotted blue), $\hat{t} = -0.35\hat{s}$ (dashed red), $\hat{t} = -0.5\hat{s}$ (solid black), $\hat{t} = -0.65\hat{s}$ (long-dashed magenta) and $\hat{t} = -0.8\hat{s}$ (dot-dashed cyan) as a function of $\sqrt{\hat{s}}$ in GeV.



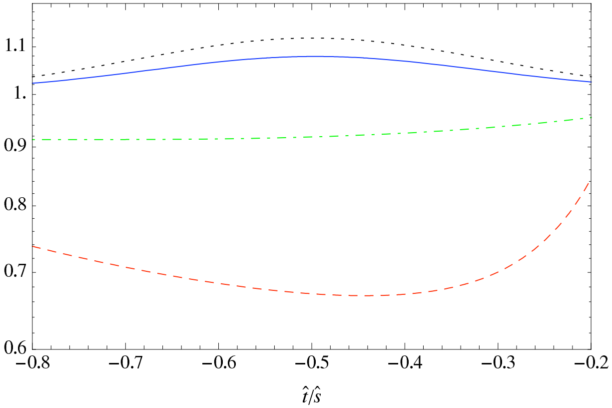
Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ at $\hat{t} = -0.2\hat{s}$, (dotted blue), $\hat{t} = -0.35\hat{s}$ (dashed red), $\hat{t} = -0.5\hat{s}$ (solid black), $\hat{t} = -0.65\hat{s}$ (long-dashed magenta) and $\hat{t} = -0.8\hat{s}$ (dot-dashed cyan) as a function of $\sqrt{\hat{s}}$ in GeV.



Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ at $\sqrt{\hat{s}} = 1$ TeV, (dotted blue), $\sqrt{\hat{s}} = 2.5$ TeV (dashed red) and $\sqrt{\hat{s}} = 5$ TeV (solid black) as a function of $-\hat{t}/\hat{s}$.



Electroweak corrections to $uu \to uu$ (dotted black), $ud \to ud$ (dashed red), $dd \to dd$ (solid blue) and $u\bar{d} \to u\bar{d}, d\bar{u} \to d\bar{u}$ (dot-dashed green) as a function of $\sqrt{\hat{s}}$ in GeV at $\theta = 90^\circ$.



Electroweak corrections to $uu \to uu$ (dotted black), $ud \to ud$ (dashed red), $dd \to dd$ (solid blue) and $u\bar{d} \to u\bar{d}$, $d\bar{u} \to d\bar{u}$ (dot-dashed green) as a function as a function of $-\hat{t}/\hat{s}$ at $\sqrt{\hat{s}} = 1$ TeV.

Conclusions

- Include electroweak corrections in a systematic way.
- Include dependence on M_W, M_Z and m_t in a spontaneously broken gauge theory including gauge mixing.
- Include Higgs corrections due to m_t.
- Can be extended to other electroweak processes such as squark production
- Purely electroweak corrections are important for LHC cross-sections.